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Status Report

# THERMAL PROCESSES FOR LIGHT OIL RECOVERY

Project BE11A, Milestone 6, FY89

By D. K. Olsen

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# THERMAL PROCESSES FOR LIGHT OIL RECOVERY

By D. K. Olsen, M. E. Crocker, P. Sarathi, and S. D. Roark

## ABSTRACT

This status report summarizes the research conducted for the U. S. Department of Energy in FY89 under Project BE11A, Thermal Processes for Light Oil Recovery, and completes milestone 6 of this project. Results from (1) evaluating the effect of temperature on capillary pressure and wettability of light oil in cores and sandpacks, (2) the steamflood oil recovery of New London crude oil, (3) a comparison of results of laboratory steamflood experiments with the results obtained using the numerical thermal simulator developed in this program, and (4) documentation in support of the U. S. Department of Energy technology transfer program with the Ministry of Energy and Mines of the Republic of Venezuela on light oil recovery by steamflooding are summarized as individual chapters .A numerical thermal simulator has been developed for laboratory applications. Wettability was found to increase with temperature. Steamflood oil performance is dependent upon wettability of the porous media.

## EXECUTIVE SUMMARY

The National Institute for Petroleum and Energy Research (NIPER) FY89 Annual Research Plan outlines research for this project, BE11A, Thermal Processes for Light Oil Recovery.[1] As compared with previous status reports, which were brief summations of the work conducted in this project for certain periods, this status report presents results and methodologies used in individual tasks within this project. Topical reports on specific, well-defined areas of work will be forthcoming when areas of work warrant coverage. Based upon the analysis of the progress at midyear FY89, modifications to the FY90 work plan were made which accommodate anticipated results. This status report describes the following:

- effect of temperature on specific core features,
- relative contribution of altered wettabilities to oil recovery efficiencies during steamflooding, and
- results to date on comparison of predicted and measured steamflood performance.

The results and conclusions from the FY89 BE11A research on Thermal Processes for Light Oil Recovery are listed below in order of priority.

1. The development and testing of a numerical thermal simulator for assisting in analysis and design of laboratory steamfloods and steamfloods with steam diverters has progressed enough to warrant preparation of a topical report for delivery in FY90.

2. The wettability of a rock surface greatly affects the recovery of light crude oil produced by steamdrive. The wettabilities of cores shift to more water-wet conditions as temperatures increase, contributing in part to the mechanism of oil production in addition to steam distillation and thermal expansion of the oil.

3. Correlations of the effect of wettability and oil production histories from 1-D steamfloods of water-wet and artificially oil-wet cores have been completed for New London crude oil. Verification of the performance with another light crude will be checked in early FY90, and the results will be reported as part of the Annex IV report.

## OBJECTIVES

The objective of this research was to improve the understanding of basic mechanisms responsible for the improvement of light oil production using steam and to use this understanding for further development of this production method. Specifically the objectives for FY89 were:

1. investigate the effect of temperature on capillary pressure and wettability in more detail;

2. determine the impact of altered wettabilities on recovery efficiencies using steam;

3. compare predicted values with laboratory-measured values of steamflood performance; and

4. support the DOE in its cooperation with Venezuela by attending the Annex IV meetings.

## BACKGROUND

The use of steam to recover light oil (API > 20°) has been reviewed as part of the NIPER FY88 research conducted under this project in a state-of-the-art review.[2] Currently, two light oil steamfloods are being conducted in the United States and both steamfloods are in Navel Petroleum Reserve fields: Teapot Dome (WY) field,[3] and the shallow oil zone of Elk Hills (CA) field.[4]

Currently, steamflooding is the primary method used for enhanced oil recovery. However, the number of steamfloods has declined from 1986.[5] EOR produced 6%, >500,000 bbl/day, of the domestic oil in 1988.[5] Thermal oil production accounted for 72.9% of the EOR oil produced in 1988 compared with 79.3% in 1986; chemical flooding contributed 3.5% compared to 2.8% in 1986; and gas-displacement production contributed 23.6% versus 17.9%.[5,6] Historically, steamflooding has been associated with heavy oil; however, heavy oil reserves account for only about 10% of the total domestic oil reserves.[7] To exploit the potential of the remaining reserves, steamflooding should be considered because of its demonstrated effectiveness in recovering oil.[8]

During FY84, NIPER conducted research in project OE4A to determine the effects of oil and rock properties on the efficiency of steamflooding for oil recovery from light oil reservoirs. Results of the work performed during that year were reported.[9-10] That project was reactivated in FY87 and continued to the present as project BE11A.

Although viscosity reduction is the most important mechanism responsible for increased recovery of heavy oil, steam distillation plays an increasingly important role as the gravity of the oil increases. Research at NIPER in FY84 demonstrated that steam distillation was the primary oil transport mechanism in light oil steamfloods and that the chemical nature of the crude oil affects the residual oil saturation after steamflooding.[11] The presence of large quantities of polar compounds in individual crude oils was found to decrease ultimate light oil recoveries.

Research conducted in FY87 and FY88 considered the effect of light oils on the gravity override of the steamfront. The results indicated that gravity override was significant in steamflooding light crude oils. In addition, oil recovery profiles of the crude used in those experiments were dependent upon the chemical composition of the crude oils and could be estimated by determining the relative composition of the light ends ($C_5$ to $C_{10}$).[11] Linear steamfloods in the laboratory were found to give unrealistically high recovery efficiencies, presumably because the effects of gravity override were minimized.[11] Results of the research conducted in FY84, 87 and 88 have been summarized.[11]

The results from the capillary pressure studies conducted in FY87 and FY88 showed the effects of varying temperature on capillary pressure for simple core-fluid systems. Synthetic oils with selectively added components were tested in FY87 to determine their effects on wettability and capillary pressure.[12] Actual crude oils, including some with selected components removed, were tested in FY88[13] to compare actual crude oils with the simplified systems tested in FY87. In all cases, an increased temperature corresponded with an increased residual water saturation and a more water-wet core. In FY89, work was planned to improve the understanding of temperature effects on capillary pressure and wettability. This work was to use special imaging techniques to investigate pore-level effects; this work will compare steamflood recovery efficiencies for different core wettabilities determined in FY88 to clarify some inconsistencies and document a more thorough investigation of the New London crude oil.

Several comprehensive reviews of thermal recovery processes, including the monograph by Prats,[14] have been published. The recent papers by Farouq Ali[15] and by Chu[16] summarize much of the technology of steamflooding. Light oil reservoirs that have performed well under waterflooding are primary targets[7,17-18] for applying the state-of-the-art of chemical flooding,[19] but they may not be suitable for light oil steamflooding. Screening criteria have not been developed for light oil steamfloods. The recovery of heavy oil by both thermal[16] and nonthermal[20] methods have been summarized; however, light oil steamflooding is still a relatively obscure technology. Major factors that influence the amount of oil recovered by EOR include the relative mobility of the reservoir oil and injected fluid, wettability characteristics of rock surfaces in the reservoir, and the interfacial tension between the injected fluid and the reservoir oil. Obviously, if plug-type flow of oil can be achieved by displacing fluid, substantial amounts of oil-in-place can be displaced. However, this is not always accomplished because of reservoir heterogeneity, because most displacing fluids travel faster through more permeable zones, and because injected fluids often have an adverse mobility ratio. Such unfavorable conditions result in bypassing significant quantities of oil which leads to low oil recovery and early abandonment of oil fields. Liquids have a more favorable mobility ratio than gases (steam) in displacing crude oil primarily because of their greater viscosity. To improve on these factors, the use of larger pore volumes of viscosified (addition of polymers to water or foams to gas) surfactant slugs (for reduction in interfacial tension) has been pursued in chemical flooding as well as profile modification methods to help block high-permeability streaks and maintain the effectiveness of the injected chemical as long as possible.

## SCOPE OF WORK

The five tasks outlined in the scope of work described in the NIPER FY89 Annual Research Plan for BE11A, Thermal Processes for Light Oil Recovery,[1] are listed below:

Task 1. Conduct characterization studies on individual cores to determine the effects of temperature on individual core properties. (Start date: October 1988. Completion date: September 1989.)

Experiments conducted during FY87 and FY88 showed that increasing temperatures appeared to alter capillary pressures and wettabilities of Berea sandstone cores in the presence of mineral oil or crude oil. However, core material is actually a composite of several types of materials, such as clays, silica, and other deposited minerals. A more detailed study of different material types will help explain how higher temperatures actually affect individual cores and will define requirements for predicting the effect of temperature on oil recovery for other types of cores.

Several factors that could alter core characteristics with temperatures have been identified. However, one or more factors having the greatest effect have not been identified. Work conducted under this task will attempt to determine which of these factors contribute significantly to the alteration of core properties with increased temperature. An initial set of experiments will be conducted to determine if clay structure or pore structure change significantly at temperatures near 300° F. Heat-treated cores will be evaluated using SEM, XRD, and capillary pressure measurements to identify permanent alterations of the clay structure; centrifuge experiments and perhaps image analysis procedures will be used to estimate the magnitude of changes in the pore structure with temperature. If most of the temperature effects on the core cannot be accounted for by the observations of these experiments, more sophisticated experiments will be developed to investigate the remaining possibilities.

Task 2. Conduct linear steamflood experiments using New London crude oil and Berea sandstone cores to determine the effect that varying wettabilities have on oil recoveries. (Start date: October 1988. Completion date: September 1989.)

Experiments conducted during FY87 and FY88 showed that increasing temperatures altered capillary pressures and wettabilities of Berea sandstone cores in the presence of mineral oil or crude oil. However, the relative contribution of these changes to overall oil recovery has not been determined. For task 2, steamflood experiments will be conducted using Berea sandstone cores at the same conditions tested for capillary pressure and wettability. Overall recoveries will be compared to determine the relative importance of different core conditions.

In FY87, Drifilm (a siloxane compound made by General Electric Company) was used to shift the wettability of Berea sandstone core to a more oil-wet state. The wettability was measured with New London crude under different wettability conditions to determine how wettability changes would affect oil recovery.

Task 3. Conduct additional capillary pressure and wettability measurements with New London crude oil. (Start date: October 1988. Completion date: September 1989.)

Preliminary studies conducted in FY88 showed that variations in pore size distribution of simple cores can substantially increase the magnitude of error bars for capillary pressure curves. A review of the broad spectrum of capillary pressure/wettability experiments conducted in FY87 and FY88 suggested that a more detailed study of New London crude oil was warranted. Additional measurements using New London crude oil are planned under task 3 to reduce these error bars and increase the certainty of our original conclusions. The work in task 3 will improve the usefulness of the capillary pressure/wettability work in reference to other laboratories.

Task 4. Compare experimental steamflooding information obtained during FY84 through FY88 with predicted values based upon fundamental principles. (Start date: October 1988. Completion date: September 1989.)

The strongest method for deriving conclusions from experimental results requires a comparison of the experimental results with expected values calculated from equations that represent known or proposed theoretical principles. Task 4 is included in this proposal to make this comparison. In FY88, a basic numerical flow simulator was assembled using fundamental principles documented in the literature.

In FY89, this simulator will be used to conduct extensive comparisons of predicted values with measured values, and sensitivity studies will be used to help direct optimum selection of operational parameters of future steamflood experiments. Modifications will be made to the simulator as needed. Such measurements as steam gravity override, residual oil saturation profiles, and oil production profiles will be compared with predicted values. The completion of this task will enable a better understanding of all laboratory experiments conducted from FY84 through FY89 at NIPER.

Task 5. Support the DOE in its cooperation with Venezuela by presenting results of this project at Annex IV meetings. (Start date: October 1988. Completion date: September 1989.)

This task will facilitate the exchange of information between DOE and INTEVEP. Particular activities within this task include attendance at joint meetings, participation in joint discussions, and presentations of results obtained from light oil research performed by this project.

## ACKNOWLEDGMENTS

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# CHAPTER 1. - CONDUCT CHARACTERIZATION STUDIES ON INDIVIDUAL CORES TO DETERMINE THE EFFECTS OF TEMPERATURE ON INDIVIDUAL CORE PROPERTIES, TASK 1.

## OBJECTIVE

The objective of this task is to conduct characterization studies on core material to determine the effects of temperature on individual core properties.

## BACKGROUND

Experiments conducted during FY87 and FY88 have shown that increasing temperatures appeared to alter the capillary pressures and wettabilities of Berea sandstone cores in the presence of mineral oil or crude oil. However, core material is actually a composite of several types of materials, such as clays, silica, and other deposited minerals. A more detailed study of the different material types will help explain how higher temperatures actually affect individual cores and will define the requirements for predicting the effect of temperature on oil recovery for other types of cores.

Several factors that could alter core characteristics with temperature have been identified; however, factors having the greatest effect have not been identified. Work conducted under this task will attempt to determine which of these factors contribute significantly to the alteration of core properties with increased temperature. An initial set of experiments will be conducted to determine if clay structure or pore structure change significantly at temperatures near 300° F. Heat-treated cores will be evaluated using SEM, XRD, and capillary pressure measurements to identify permanent alterations of clay structure; centrifuge experiments and perhaps image analysis procedures will be used to estimate the magnitude of changes in pore structure with temperature. If most temperature effects on cores cannot be accounted for by observations of these experiments, more sophisticated experiments will be developed to investigate the remaining possibilities.

## EXPERIMENTAL PROCEDURE

### Core Samples

Berea sandstone core samples were from the Cleveland Quarry, Amherst, Ohio. Permeability for the Berea cores ranged from 200 to 700 md. The core size used in the corefloods was 1.0 in. diameter and varied in length from 3 to 21 in. depending upon experiments.

### Experimental Brine and Bead Slurry

Reagent grade chemicals were used in all experimental work. The brine was made using Milli-Q™ water. A dilute brine solution was used for these experiments (1% NaCl + 2% KCl). This brine was used to assure that there was no brine-induced core damage throughout the test period. The brine was filtered through a 0.45-micron filter and degassed before use.

## Dynamic Fluid Flow System

A diagram of the fluid flow apparatus is shown in figure 1. To simulate reservoir pressure conditions, the core sample is encased in a high-pressure stainless steel cell. The core cell is filled with fluid (usually water), which provides the means of simulating an overburden pressure on the core with a hydraulic pump. The core is physically separated from the overburden fluid by a rubber sleeve.

To duplicate linear flow rates found in subsurface injection systems, the high-pressure pumping system must provide a constant flow rate, 1 ft/d (0.3 m/d) or greater, with negligible pulsation at operating pressures approaching 3,675 psi (25.3 MPa). A Waters HPLC pump capable of 6,000 psi (41.4 MPa) pressure and reservoir flow rates is used for these tests.

The pressure applied to the outside of the core cell contained in the rubber sleeve simulates the overburden pressure in a reservoir and prevents leakage of the fluids pumped through the core as the internal pressure of the system is increased. The overburden pressure is simulated using a standard hydraulic pump with a pressure capability of at least 5,000 psi (34.5 MPa).

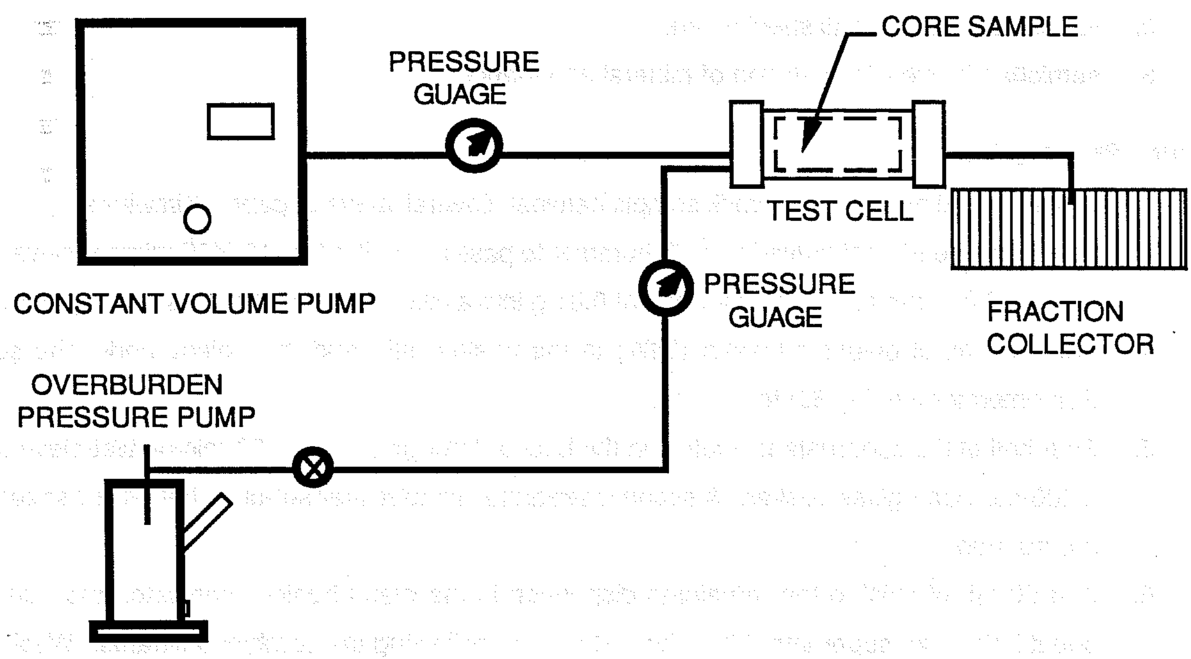


FIGURE 1. - Schematic of coreflooding apparatus.

**Fluid Flow System Operation**

Dynamic flow experiments were performed using the following experimental conditions:

| | |
|---|---|
| Overburden pressure, psia............. | 150 higher than injection pressure |
| Injection pressure, psia.................. | 0 |
| Injection rate, mL/min...................... | 10 |
| Temperature, °F.............................. | 75 |

The core was mounted in the cell, the constant rate pump was primed, and a simulated overburden pressure 150 psi (1034 kPa) above injection pressure was applied around the core. The system was switched to the bypass mode. The pump was set to the desired flow rate, and brine was pumped through the core. Effluent samples were taken at specific time intervals for pH evaluation.

**X-Ray Diffraction Analysis (XRD)**

Interpretation of X-ray diffractograms requires several steps during which the peaks of the diffractogram are converted into significant geologic data.[1] The following steps are followed for mineral identification:

1. measurement of molecular plane repeat distances (d-spacings),
2. identification of mineral species, and
3. semiquantitative interpretation of mineral abundance.

**Sample Preparation**

1. Place approximately 15 g of rock sample between several layers of paper (Kimwipes).
2. Crush sample (do not pulverize) with hammer to pass through a No. 40 (425 micron) sieve.
3. Weigh 10 g of the sample to the nearest 0.01 g into a clean 600-mL stainless steel beaker.
4. Add 300 mL of deionized water (DIW) to the beaker, stir, and then place under the sonic dismembrator (setting 60) for 30 sec.
5. Pour half of the supernatant solution in the beaker through a wetted 30-micron wet-sieve atop a 400-mL clean glass beaker. A second, separate sieve/beaker set-up is helpful for speeding up this step.
6. Add 50 mL of DIW to the remaining dispersion in the metal beaker; sonicate, and pour off about half of the supernatant into the wet-sieves, collecting the combined filtrates. Wash the material on the sieve with DIW.
7. Repeat step 6 until the supernatant in the metal beaker is clear.
8. Quantitatively transfer, with the help of a squeeze bottle filled with DIW, the remaining material in the metal beaker to the wet-sieves. Wash the material on the screens with DIW. Retain the filtrates (<30 micron material) in the beakers.

9. Quantitatively transfer, using a squeeze bottle, the material (>30 microns) on the sieves to a Teflon™ evaporating dish. Decant excess water from the dish. Dry this fraction of the sample at 100° C overnight. Cool and weigh material.
10. Vacuum filter onto a porous (0.5-micron) stainless steel sample plate sufficient suspension (<30 micron) to obtain a thin, uniform cake of clay material on the plate. The suspension should be stirred to suspend the clays and added nearly dropwise to the filter to assure that a representative sample is collected on the plate. Save the remaining <30 micron sample in the beakers.
11. Dry the plate (continuing <30 micron sample) for 1 hr at 300 C and cool in a dessicator.
12. Attach the sample plate to a glass slide.
13. Obtain the X-ray diffraction pattern for this sample from 2° to 37°, 2Θ.
14. Remove the sample from the glass slide and place in an ethylene glycol chamber at 60° C overnight.
15. Obtain the XRD scan on this glycolated sample (2° to 37°, 2Θ).
16. Remove the plate from the glass slide and place it in the muffle furnace at 600° C for 1 hr. Cool the sample in a dessicator.
17. Obtain the XRD scan on the sample (third scan).
18. If the XRD patterns for the <30 micron fraction are of poor quality (peaks small, broad and/or unresolved), centrifuge the remaining filtrate at 1000 RPMS for 3 min to obtain the <2 micron size fraction (supernatant) and follow steps 10 through 17.

## Scanning Electron Microscopy (SEM)

The SEM was used to provide visual images of the core samples. The SEM analyses were conducted utilizing procedures described by Postek et al.[2] The SEM is of value in determining sample morphology, surface mineral composition, and type and location of clays. Comparison of conditions of core before and after an experiment aids in determining potential rock-fluid interactions.

The electron microscopic characterization of the samples was conducted using an International Scientific Instrument Super IIIA SEM. The samples used for SEM/EDS analyses were prepared from small chips of the rock to permit a fresh surface for analysis. The samples were examined at a low magnification to obtain an overview of their general characteristics and clay distribution. After identification of significant features such as clay particles, pore throats, and beads, the magnification was increased sufficiently to show detailed features of interest, and a photograph was made.

## EXPERIMENTAL RESULTS AND DISCUSSION

### Capillary Pressure/Wettability

A literature evaluation indicated that similar work by Shaw et al.,[3] has recently been conducted on the effects of firing on Berea sandstone. In this work, variations of clays, SEM morphology, and pH were evaluated. Since the cores used in this work were heated for 16 hours to attain equilibrium before each high-temperature capillary pressure/wettability experiment and an additional 8 hours during the centrifuge run, it was believed that evaluations of possible changes in cores during this time span might provide additional insight as to why changes in capillary pressure and wettability were occurring.

### Core Characterization Studies

Mineralogical changes associated with temperature were the first variables to be evaluated because clays are known to be significantly altered by increases in temperature, and this alteration could possibly result in changes in residual water saturation.[4] X-ray diffraction analyses were conducted on a series of Berea sandstone cores that were cored from the same block. Groups of cores were heated for 24 hours to 200°, 300°, 400° and 500° F for an evaluation of mineralogical differences that could be attributed to increases in temperature. The results of mineralogical analyses for these cores are shown in table 1. Since X-ray diffraction is a semiquantitative method, variations, as noted in the analyses, were within the accuracy of the test. However, the core heated to 500° F indicated that some mineralogical changes were occurring within the core. Analyses by X-ray diffraction indicated a threshold temperature above which clay degradation occurs but did not indicate possible reasons for an increased water-wettability for cores heated to 200° to 300° F.

Scanning electron photomicrographs of unfired and fired Berea core material were taken to provide additional insight. These photomicrographs show a loss of clays in the pore throat areas for the fired cores. There appears to be no evidence of microfractures or other core deterioration resulting from the firing. Disaggregation of clays from water loss at the fired temperature could possibly account for an increase in residual water saturations, but in the SEM photomicrographs of the Berea cores examined, this

TABLE 1. - X-ray diffraction analysis of Berea core, wt %

| Sample, °F | Quartz | Feldspar | Calcite | Dolomite | Siderite | Kaolinite | Chlorate | Illite/mica | Illite/ smectite | Hematite |
|---|---|---|---|---|---|---|---|---|---|---|
| 200 | 89 | 4 | tr | 2 | 2 | 2 | tr | 1 | - | - |
| 300 | 90 | 3 | tr | 2 | 2 | 2 | tr | 1 | - | - |
| 400 | 89 | 4 | tr | 2 | 2 | 2 | tr | 1 | - | - |
| 500 | 93 | 2 | tr | 1 | - | tr | - | 1 | 1 | 2 |

does not appear to be the reason for the increase in residual water saturation as run temperatures are increased. XRD analysis of the clays in the fired Berea core provided additional confirmation of this conclusion.

Capillary pressure experiments (brine/nitrogen at ambient temperature) were conducted on adjacent cores heat treated in the same manner (200° to 500° F). Actual experiments were all run at 75° F. Results of these experiments are listed in table 2, but no definite pattern is noted for this set of experiments. The final $S_{wr}$ of each run was used as a means of comparing individual cores.

Adjacent Berea cores were heated for 24 hours to 140°, 200°, 300° and 500° F, cooled, and then flooded (10 mL/min) with deionized water at ambient temperature (pH 3.53, using the equipment shown in figure 1). A graph of the pH of the effluent from these core is shown in figure 2. The pH of the effluent was highly basic (as compared to that of injected water) for the first 200 to 500 mL of effluent input for all cores tested. Only after large pore volumes of water were injected did the pH decrease. After considerable flooding, (360 minutes, 450 pore volumes) each core was shut-in overnight (16 hours - comparable to the equilibration time). In each case, the pH of the system increased significantly toward the basic state. There was a direct correlation between an increase in pH upon standing and the temperature at which the cores were heated.

Shaw et al.[3] fired Berea sandstone to a considerably higher temperature (1,000° C, 1,832° F). Their analysis of the ionic content and conclusions indicated that heating had formed calcium oxide, which upon flooding with brine produced calcium hydroxide that yielded the high pH. The same mechanism may be responsible for these observed pH changes. Additional work is needed to define the causes for pH changes and the effect of this on capillary pressure and wettability measurements.

TABLE 2. - Residual water saturations derived from capillary pressure (brine/nitrogen) for Berea cores heat-treated at various temperatures

| | 75° F | | 200° F | 300° F | 400° F | 500° F |
|---|---|---|---|---|---|---|
| $S_{wr}$, % | 20.0 | | 20.49 | 19.34 | 20.16 | 20.08 |
| | 18.1 | | 20.54 | 18.74 | 18.83 | 20.49 |
| | 18.6 | | 20.56 | 19.24 | 21.82 | 20.21 |
| | 18.58 | | 20.40 | 18.22 | 19.21 | 20.20 |
| | 19.65 | | 20.50 | 18.80 | 19.09 | 20.25 |
| | 19.25 | | 20.56 | 19.66 | 19.53 | 21.94 |
| Avg | 19.05 | | 20.51 | 19.00 | 19.77 | 20.53 |
| Avg for all | | 19.77 | | | | |
| Deviation from avg of all | -0.72 | | +0.74 | -0.77 | 0.0 | +0.76 |

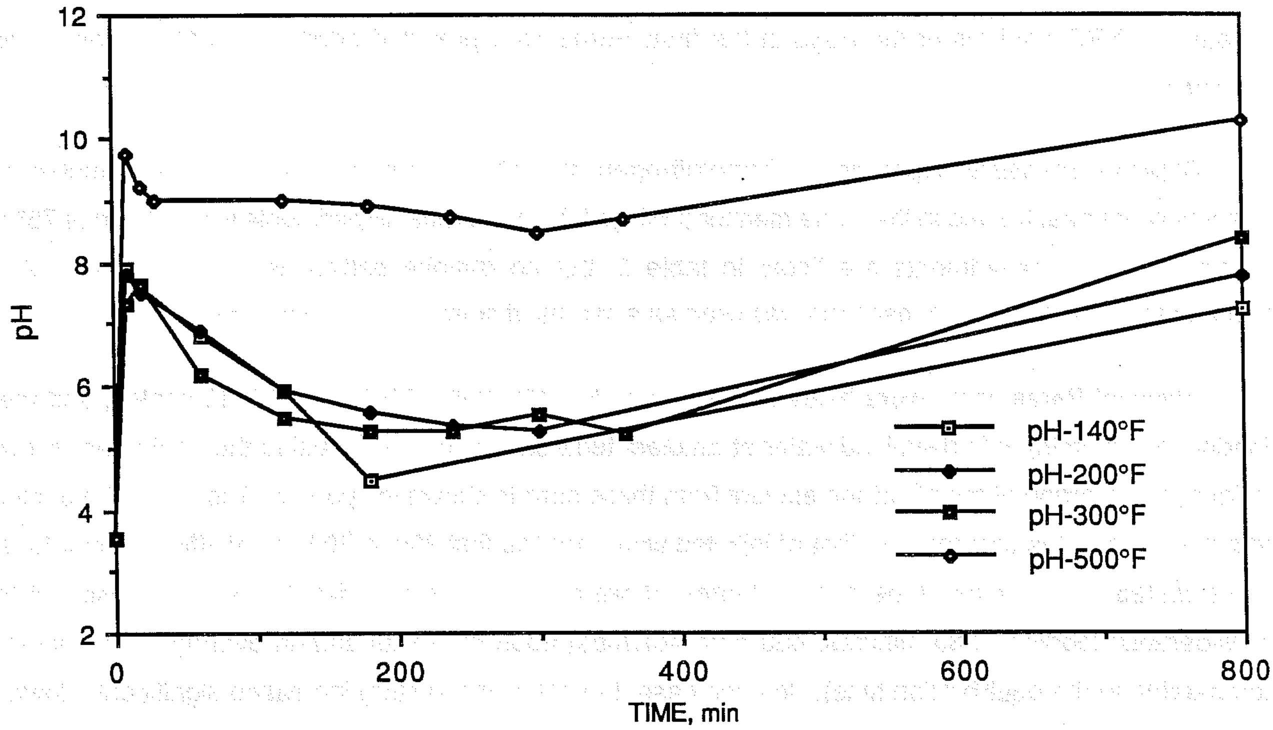


FIGURE 2. - The pH of effluent from heated Berea sandstone cores.

## DISCUSSION

Characterization studies on core material to determine the effect of temperature on individual core properties included X-ray diffraction, SEM analysis, and specialized coreflood procedures. X-ray diffraction analysis was made on cores fired to 200°, 300°, 400°, and 500° F. These results did not provide indications of any major changes in the mineral or clay analysis for samples up to 400° F. The 500° F core sample did have subtle changes in mineralogy and clay composition upon comparison to the cores fired at the lower temperatures. However, one clay type that is more prevalent in the 500° F sample is illite/smectite which should be most affected by a temperature increase.

The SEM evaluations of the unfired and fired core sample confirmed the XRD results. Disaggregation (dewatering) of clays are noted in the fired sample, but this does not appear to be a major mechanism for an increase in water saturation. For laboratory experiments, fluids are present, so this mechanism is assumed not to occur during testing.

The residual water saturations (table 2) provided results similar to the XRD and SEM analyses. Final residual water saturations were again essentially the same for the 75° and 500° F runs, indicating that temperature increases alone are not responsible for increases in residual water saturations.

Specialized coreflooding on fired core samples did provide insight into chemical reactions occurring during laboratory testing. These floods are presumably in excess of normal laboratory operating parameters as up to 450 pore volumes was injected through the samples. The pH of all samples had a dramatic increase from that of the deionized water injected. The pH values were still up to 6 pH units higher after flooding for over 450 pore volumes.

Additional evaluations are needed to further define the chemical process that is occurring during the corefloods. These could include ICP/AES analyses of effluents to determine exact chemical content.

## RESULTS AND CONCLUSIONS

1. Specialized coreflooding on fired core samples indicate effluent pH values that were up to 6 pH units higher than the input values.

2. Capillary pressure experiments on fired cores resulted in residual water saturation that were essentially the same for all temperature ranges. These results indicate that run temperatures alone are not responsible for increases seen in residual water saturations.

3. XRD and SEM analysis of fired cores did not indicate any major changes in the mineralogy or clay content for samples up to 400° F. The 500° F fired core did have subtle changes in mineralogy and clay content.

## RECOMMENDATIONS

1. Additional specialized core analyses should be performed using fired core. These analyses would further define the chemical process that is occurring during the flooding process. Effluent samples would be monitored using ICP/AES.

2. Detailed image analysis of fired core would provide additional information concerning changes in porosity and permeability for the fired core on a microscopic level.

3. The above evaluations should be extended to other core types as only Berea sandstone was evaluated.

4. A larger number and more sophisticated XRD and SEM analyses should be performed to provide a larger data base for final conclusions.

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## CHAPTER 2. - CONDUCT LINEAR STEAMFLOOD EXPERIMENTS USING NEW LONDON CRUDE OIL AND BEREA SANDSTONE CORES TO DETERMINE THE EFFECT THAT VARING WETTABILITIES HAVE ON OIL RECOVERIES, TASK 2.

### OBJECTIVE

Conduct linear steamflood experiments using New London crude oil and Berea sandstone cores to determine the effect that varying wettabilities have on oil recoveries.

### BACKGROUND

Light oil recovery with steam from water-wet and oil-wet sands has not received as much attention as recovery by waterflooding. A monograph by Willhite[1] provides an excellent background for the physics and chemistry behind previous research and field performance of waterfloods and hot waterfloods.[1] Ouettier and Corre[2] conducted hot water and steamflood laboratory experiments under reservoir conditions (silty limestone) on a 24° API crude to obtain a better understanding of steam displacement mechanisms and supply essential data for numerical simulation of a steamflood pilot. Many of the factors affecting light oil steamflooding have been evaluated[3-4] and simulated,[5] but the effect of wettability has not been addressed. This task was to compare oil recoveries from 1-D steamfloods of light New London crude oil from Berea sandstone cores at the same conditions tested for capillary pressure and wettability, task 3.

### EXPERIMENTAL PROCEDURE

Linear steamfloods were conducted in a high-pressure, heavy-wall Hassler coreholder that had been modified at NIPER with pressure and imbeded temperature ports, as shown schematically in figure 1. This model uses 1.5-in.-diameter cores that have a variable length up to 26 in. long. The 1-D coreholder, when mounted in place of the 2-D steamflood model, is a part of the steamflood apparatus, as shown in figure 2. Differential pressures across the model are measured by Validyne transducers (model DP215 with CD233 digital demodulators) connected to strip chart recorders. Temperature measurements are taken from an array of ports outside and along the core with an Omega model 199 scanner.

Overburden pressure is maintained by nitrogen gas. Backpressure in the model is maintained with a Badger pneumatic control valve (regulated with a Doric DC7100 Microprocessor controller) which can be set within 1% of the desired backpressure. The built-in, self-tuning feature in the microprocessor reduces pressure pulses, but an optimum backpressure valve without pulsing has not been achieved. Solids are removed by Nupro in-line filters (60 micron). These are set up in parallel to allow flow to be diverted to a standby filter while filter elements are cleaned or replaced. Produced fluids pass through a water-cooled condenser before being collected by manual switching of graduated cylinders or the use of a fraction collector (Gilson FC-100 microfractionator). Constants volume (<10 mL) or time measurements were

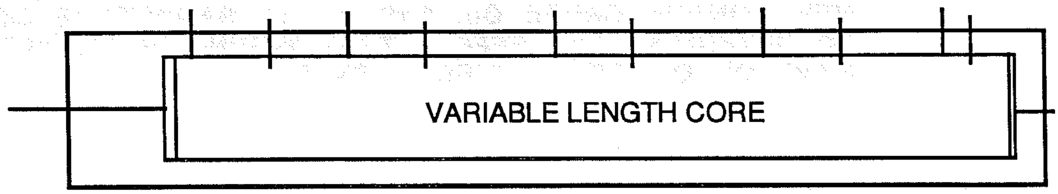


FIGURE 1.- Schematic of 1-D coreholder.

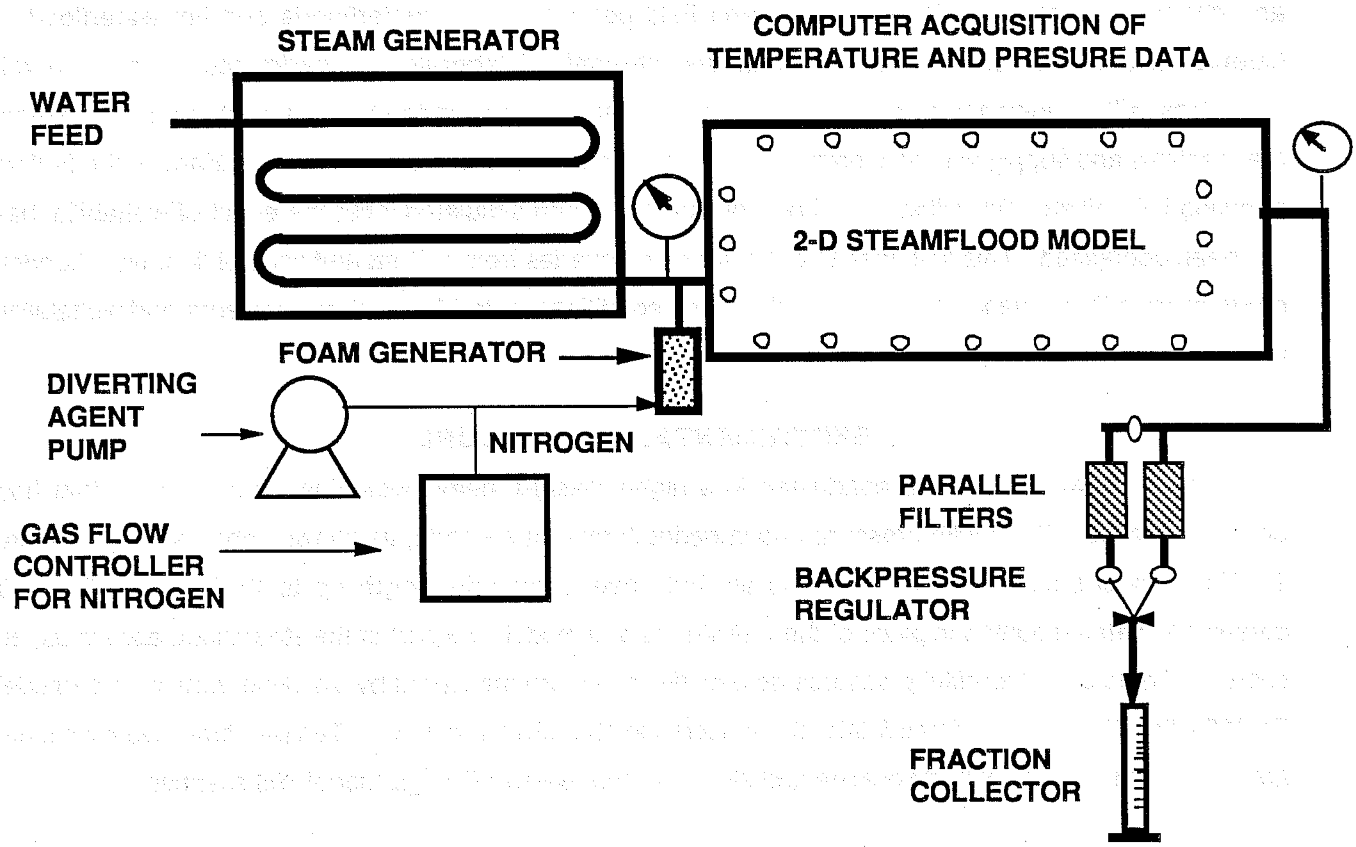


FIGURE 2.- Schematic of steamflood assembly.

conducted to obtain finer oil-water ratios with the fraction collector. Produced fluids are usually emulsified, and this year chemical treating - emulsion breakers were used to obtain clean fluids. (Data from previous oil recovery experiments may have been optimistic due to reporting of some oil-water emulsions as clean oil.)

Steam is generated by pumping deionized water with a Milroyal (model A) metering pump through a (Lindberg 54571) tube furnace containing stainless steel tubing that has been coiled around a stainless steel pipe for increased heat transfer. The furnace is equipped with a controller which allows local control or remote control through a computer. The temperature in the furnace can be controlled from ambient to 1,000° C. A constant supply of water for the pump reservoir is assured by means of a (Dyna-Sense 7188) automatic level controller. Steam generated from this assembly is superheated. Spring-loaded check valves are placed in the steamflood system to act as safety, pressure-relief devices.

The core saturation procedure and flooding operation have been described previously.[6] Artificially oil-wet cores were obtained using a gas-phase treating procedure described in the experimental section of chapter 4. Properties of the oils used in this study are listed in tables 1 and 2. The Wade oil is from the Cities Service Wade lease, Ponotoc County, Oklahoma; the D. C. oil is from B & N Oil lease in Delaware-Childers field, Nowata County, Oklahoma; and the New London crude oil was obtained from Murphy Oil, Cotton Valley formation, Union County, Arkansas, King Well No. 1.

TABLE 1. - Properties of light crude oils used in this study

| Oil | Gravity, API° | Viscosity, cP | Asphaltenes, wt % | Polar, wt % | Saturates, wt % | Aromatic, wt % |
|---|---|---|---|---|---|---|
| Wade | 30.3 | 7.2 | - | - | - | - |
| Delaware-Childers | 34.5 | 6.1 | - | - | - | - |
| New London | 33.0 | 6.9 | 1.7 | 9.6 | 37.2 | 51.2 |

TABLE 2. - Simulated distillation (°F) by gas-chromatography

| Oil | 10% | 20% | 30% | 40% | 50% | 60% | 70% | 80% |
|---|---|---|---|---|---|---|---|---|
| Wade | 305 | 444 | 542 | 626 | 711 | 798 | 890 | 1,000 |
| Delaware-Childers | 283 | 378 | 457 | 540 | 624 | 710 | 804 | 907 |
| New London | 272 | 385 | 478 | 562 | 648 | 741 | 847 | 976 |

## EXPERIMENTAL RESULTS AND DISCUSSION

### Linear Steamfloods Using New London Oil and Berea Sandstone

The 1-D steamfloods are characterized by three parts: initial warm waterflood, lag period where the connate water and oil are heated to steamflood temperature, and steamflood distillation of the light crude followed by steam breakthrough after which only traces of oil are produced. Figure 3, run number 1, shows results of a steamflood in a water-wet core which was terminated at the end of the hot waterflood or when a water-oil ratio exceeded 200. This resulted in 20% of the OOIP being produced.

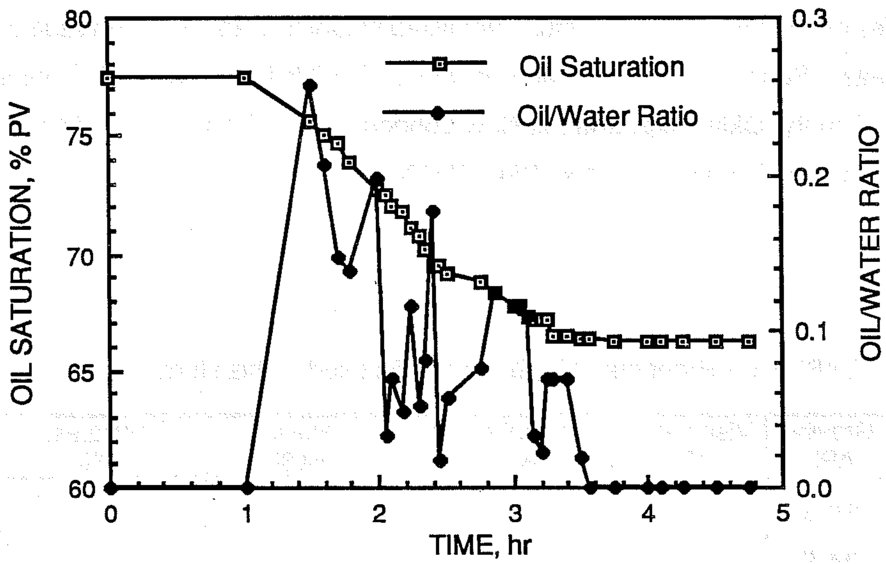


FIGURE 3. - Oil production and the change in pressure drops with respect to time for a hot waterflood of New London crude, run 1 (water-wet core).

Figures 4 and 5 show results of continuing a steamflood and show that after a hot waterflood, there is great thermal input before the next major oil bank. The initial 4 hours of the 15-hour steamflood corresponded with production from the hot waterflood phase and produced 24.5% of the OOIP. As heat increased during the following 4 hours, no significant oil was produced, and the water-oil ratio exceeded 600. During the next 2 hours, the overall pressure drop across the model increased from 5 to 80 psi. While the injection pressure was maintained at 160 psig, the outlet pressure had to be reduced from 155 to 80 psig, figure 5. This pressure reduction caused a lowering of the boiling point of water in the core, and the hot water in the core flashed to steam causing a boost in production. Additional oil recovery in excess of 40% of the hot waterflood was produced in 2 hours, whereas no oil had been produced during the previous 4 hours. A reduction in the water-oil ratio from 600 to less than 10 was observed in these 2 hours, figure 5. The performance during this time period supports claims made in the patent application for "Flash-Driven Steamflooding," submitted by this research group. Good oil production continued for the next 3 hours until steam breakthrough. Steam distillation was the main mechanism for oil recovery of this light oil.

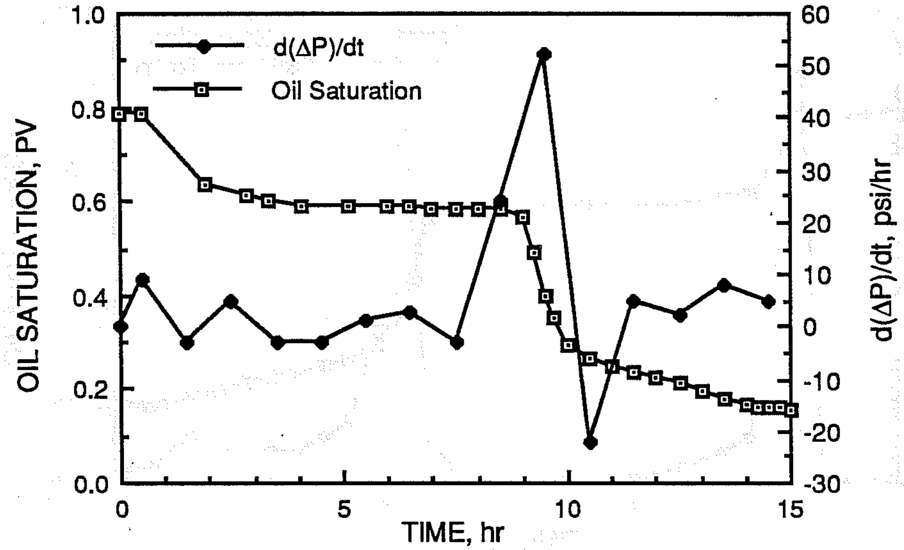


FIGURE 4. - Oil production and the changes in pressure drop with respect to time for the 1-D steamflood.

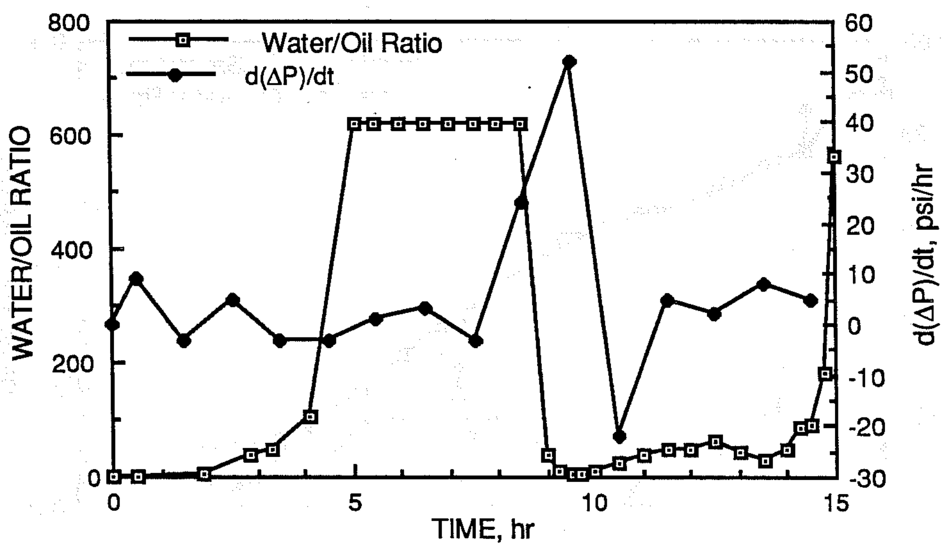


FIGURE 5. - Water-oil ratios and changes in pressure drop with respect to time for a 1-D steamflood.

The behavior of the series of steamfloods with New London crude oil with cores of various wettabilities is shown in figures 6-8. The steamfloods from the water-wet Berea show both a lower final residual oil saturation and an accelerated production during the entire time of production compared to the runs using the silylated Berea sandstone.

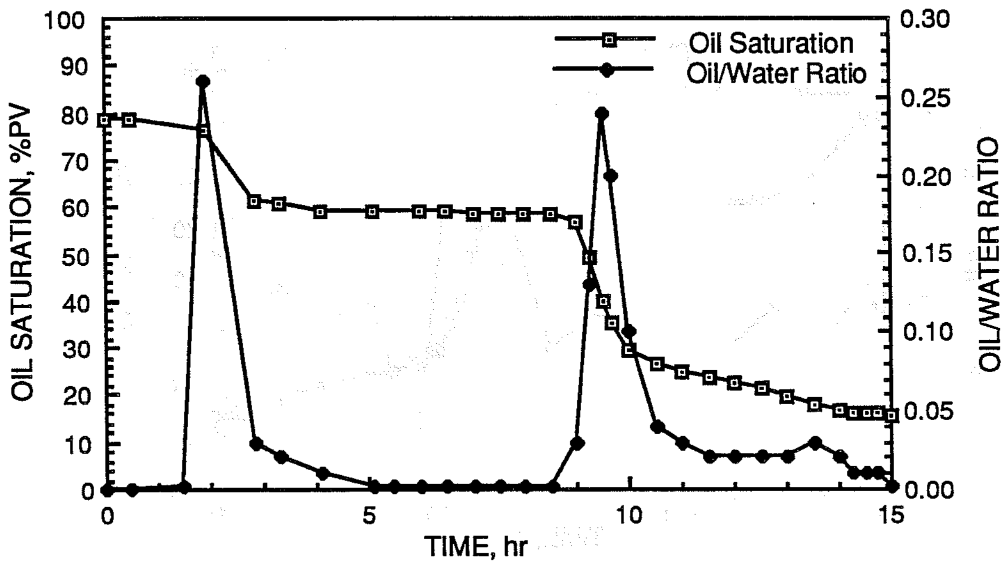


FIGURE 6. - Oil production and changes in pressure drop with respect to time for water-wet 1-D steamfloods with New London crude oil, run 3.

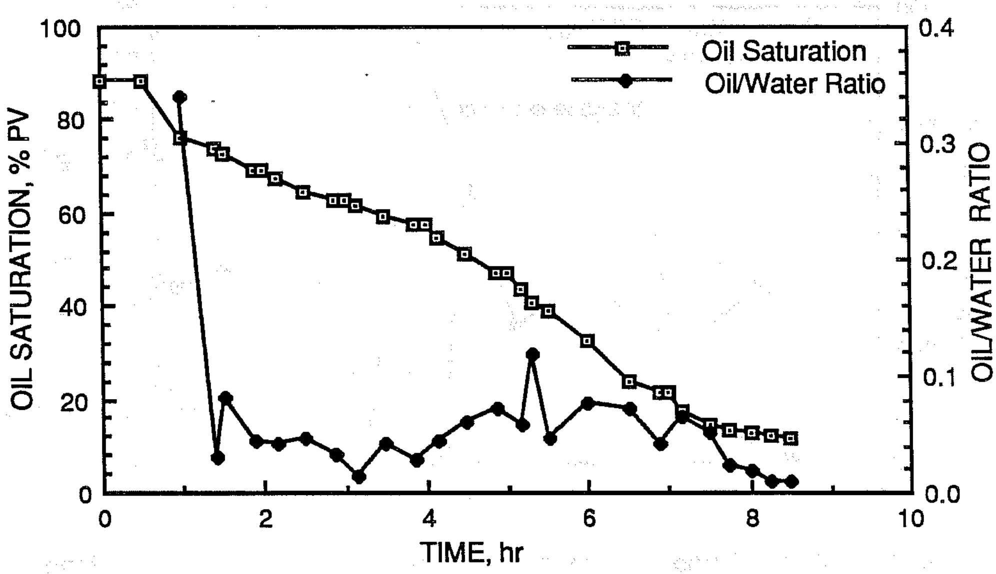


FIGURE 7. - Oil-water ratios and changes in oil saturation with respect to time for oil-wet 1-D steamfloods with New London crude oil, run 4.

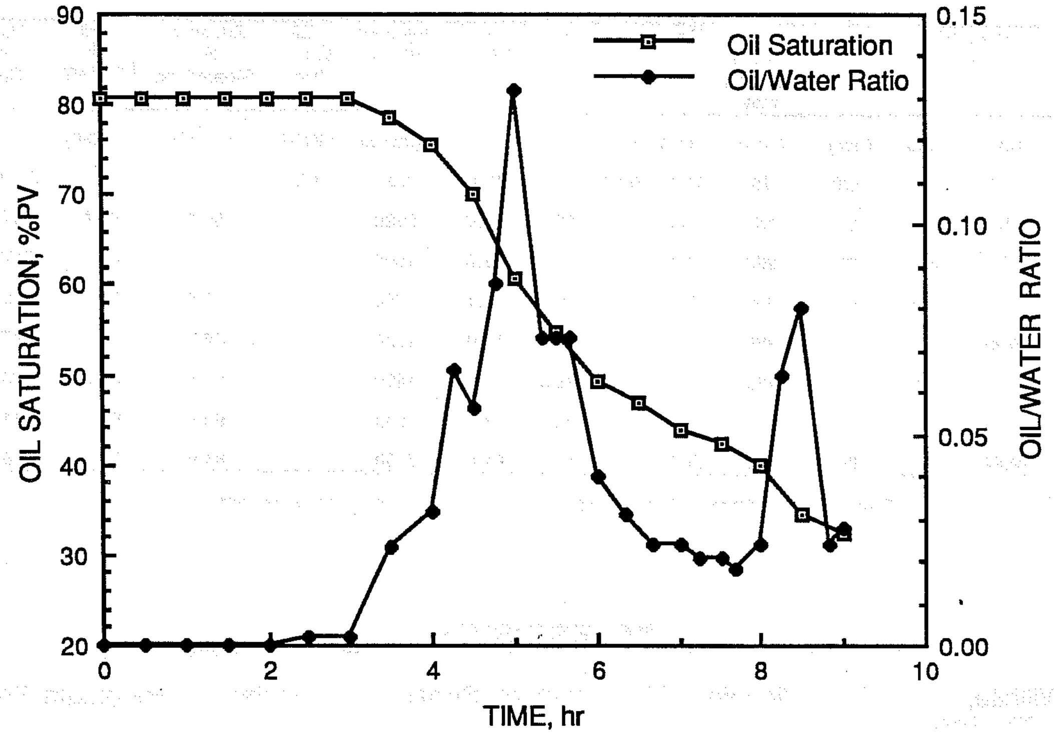


FIGURE 8. - Oil-water ratios and changes in oil saturation with respect to time for an intermediate-wet 1-D steamflood with New London crude oil, run 5.

The 1-D steamfloods that were completed this year using New London crude oil and water-wet or artificially oil-wetted Berea sandstones are summarized in table 3.

## CONCLUSIONS AND RECOMMENDATIONS

Preliminary data on New London crude recovered via steamflood show the wettability of the rock matrix greatly influences oil production. The water-wet steamfloods required more energy input, and oil production was behind after a short period of time as compared to the oil-wet scenario. Verification of these results with another light crude oil and establishing that these are not artifacts produced by the silylation of the rock are needed to confirm these conclusions. If the conclusions are supported it would mean that there is great potential in steamflooding light crudes from oil-wet reservoirs which typically give up their oil very slowly. Many are currently stripper operations or have been abandoned because they produce little oil from waterflooding.

TABLE 3 - Summary of the Light Oil 1-D Steamfloods

| Run | Core | Wettability Index | | Back-pressure | Average steam injection rate | $S_{OI}$ | $S_{OW}$ | $S_{OF}$ | Fluid Water | Injected Steam | Oil Water-flood | Recovery By Steamflood | Total Oil Recovery | Date of Run |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| No. | No. | Start | End | (psig) | (g/hr) | (% PV) | (% PV) | (% PV) | (% PV) | (grams) | %OOIP | %OOIP | (%OOIP) | |
| 1 | 1 | +0.41 | | 120 | 75 | 78.5 | 68.2 | | 2.0 | 284 | 14.5 | | 14.5 | 5/12/89 |
| 2 | 1 | Same core | | 90 | 150 | 78.6 | | 15.8 | 15.9 | 2230 | | 80.0 | 80.0 | 5/17/89 |
| 3 | 1 | Same core | | 90 | 250 | 78.6 | | 57.1 | 12.8 | 1800 | | 27.3 | 27.3 | 7/6/89 |
| 4 | | | +0.47 | 90 | 250 | 78.6 | | 38.6 | 13.1 | 1840 | | 50.9 | 50.9 | 8/8/89 |
| 5 | 2 | -0.82 | | 90 | 250 | 88.5 | | 11.8 | 13.9 | 1800 | | 84.4 | 84.4 | 8/17/89 |
| 6 | 2 | | -0.46 | 90 | 250 | 88.5 | | 38.5 | 11.0 | 1430 | | 56.5 | 56.5 | 8/23/89 |
| 7 | 3 | +0.41 | | 90 | 250 | 67.6 | | 4.3 | 12.7 | 1840 | | 93.6 | 93.6 | 9/11/89 |
| 8 | 4 | -0.82 | | 90 | 250 | 76.7 | | 11.9 | 14.4 | 2100 | | 84.6 | 84.6 | 9/18/89 |

Cores 1 and 3 are water-wet fired Berea Sandstone. Cores 2 and 4 are oil-wet silylated fired Berea sandstone.

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# CHAPTER 3. - CONDUCT ADDITIONAL CAPILLARY PRESSURE AND WETTABILITY MEASUREMENTS WITH NEW LONDON CRUDE OIL, TASK 3.

## OBJECTIVE

The objective of this task is to conduct additional capillary pressure tests to reduce the magnitude of error bars found in previous testing, thereby increasing the certainty of our original conclusions.

## BACKGROUND

Preliminary studies conducted in FY88 showed that variations in pore size distribution of sample cores can substantially increase the magnitude of the error bars for capillary pressure curves. A review of the broad spectrum of capillary pressure/wettability experiments conducted in FY87 and FY88 suggested that a more detailed study of New London crude oil was warranted. Additional measurements, using New London crude oil, were undertaken to reduce the magnitude of the error bars, thereby increasing the certainty of our original conclusions. This work was designed to improve the usefulness of the capillary pressure/wettability work for other laboratories.

## EXPERIMENTAL

The procedure for operation of a high-temperature capillary pressure - wettability centrifuge has been described previously.[1] A series of experiments was conducted on both water-wet Berea sandstone and an artificially oil-wet Berea sandstone prepared by silylation. The water-wet series is described in the results and discussion section. The oil-wet series was conducted in the same manner once the cores were prepared.

Silylation of the core plugs, glass plates, long cores (used in task 2) and crushed Berea sandstone (used in project BE11B) were prepared via gas-phase silylation. Our previous experience using liquid-phase[2] (dichlorodimethylsilane or dichlorodiphenylsilane as 7% solution in hexane) or Drifilm indicated the process produced nonuniform wettability in cores prepared for higher temperature waterflood applications. The surface wettability seemed to revert to water-wet after multiple pore volumes of hot water (200°F) were pumped through cores as indicated by oil recovery profiles in chemical floods. A gas-phase silylation procedure similar to that used by Takach et al.[3] for their glass plates was undertaken.

Initially a glass pressure vessel was used at 210° F and 5 psig for confinement, but the treating conditions yielded plugs that had a surface coating only as exhibited by the easy conversion of the plugs to a water-wet condition. A 6-foot-long by 3-inch-diameter stainless steel pressure vessel was then constructed (fig. 1) which could be heated uniformly in a tube furnace to 550° F. Cores (fired or unfired), glass plates, or crushed stone were placed in the pressure vessel and sealed. The metal-to-metal O-ring seal when carefully torqued could provide a seal necessary for evacuation to 0.5 torr and later could

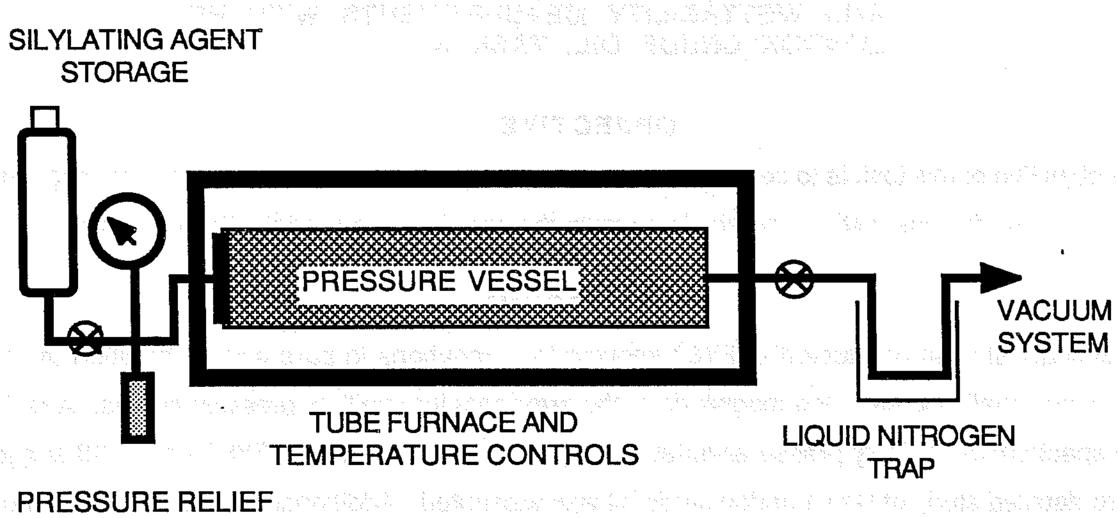


FIGURE 1. - Schematic of pressure vessel for gas-phase silylation of core material.

withstand a pressure buildup of 150 psi at the operating temperature. The vessel was loaded with core, evacuated, and heated to 200° F for at least 24 hours and then allowed to cool. Then bis(dimethylamino)dimethylsilane (Aldrich Chemical, CAS.No. 3768-58-9) was introduced as 30 mL aliquots, once when cool, once at 100° F, and then again at around 200° F as the reaction vessel was heated. Upon addition of the last aliquot, the valve to the vacuum pump was closed, and the vessel was allowed to pressurize. The vessel was slowly heated to 550° F over 4 hours, then held at that temperature for 3 hours, and then allowed to cool overnight. Pressure buildup during three of the runs did not exceed 140 psi and did not cause the pressure relief valve(set at 150 psi) to open.

## EXPERIMENTAL RESULTS AND DISCUSSION

### Capillary Pressure Evaluations

The objective of the first section of the task was to obtain additional capillary pressure data to reduce the magnitude of the error bars in capillary pressure curves and to increase the certainty of our initial conclusions regarding a shift towards higher residual water saturation as temperature increases in water-wet cores. Three different systems of water-wet capillary pressure curves were evaluated: (1) a simple nitrogen/brine system, (2) a heavy mineral oil/brine system, and (3) various crude oil/brine systems. To minimize variables associated with cores, one set of cores was used for each experimental series (75°, 200°, and 300° F). The experiments were conducted in the following order: (1) using the nitrogen/brine; (2) using mineral oil/brine (which required only a resaturation procedure); and (3) using crude oil/brine (A Dean-Stark type cleaning was conducted after the mineral oil/brine experiment before the crude oil/brine experiment was begun). Using this sequence, the variables normally associated with cores should be minimal while producing the maximum amount of reliable data. Preliminary studies conducted in FY88 showed that variations in pore size distributions of cores could substantially increase error bars in the mineral oil/brine capillary pressure data reported for the Berea sandstone cores (at 95% confidence level), as shown in figure 2.[4] Results of the capillary pressure measurements on the mineral oil/brine system are shown in figure 3. The residual water saturation for the mineral oil/brine system was significantly different at the three temperatures tested, and when compared with figure 2, a significant improvement was noted because of additional experiments and a reduction of variables affecting the system. Comparable significant differences of residual water saturation for the nitrogen/brine and New London crude oil systems were obtained at 75°, 200°, and 300° F.

Previous capillary pressure work was conducted at four temperatures: 75°, 150°, 250°, and 350° F. In the current series, 75°, 200°, and 300° F were selected. One goal of the research was to determine if specific temperature levels were responsible for any experimental variations. In each of the capillary pressure measurements, 250 psig of nitrogen was used to reduce sample vaporization. As shown in figure 2, the confidence interval for the 75° F run was greater than that of the 300° F experiments. To improve precision of the experiments, each run at each temperature was also closely monitored for material balance, and the result was eliminated from further evaluation if the material loss was too high. A comparison of figure 2 with figure 3 indicates that our laboratory experimental technique has improved.

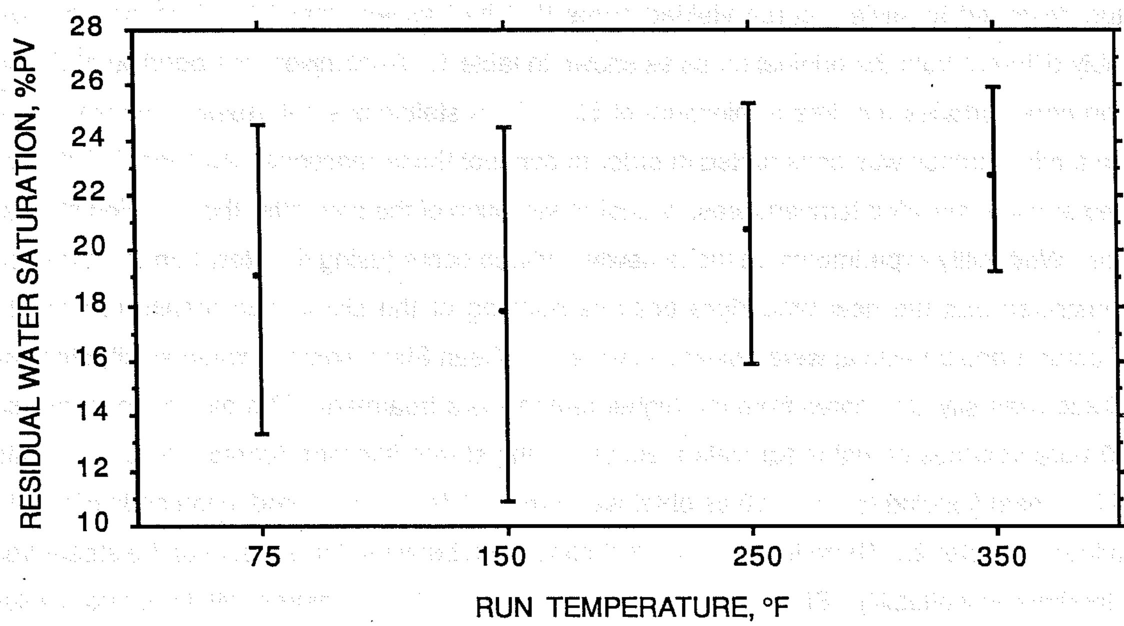


FIGURE 2. - Residual water saturations from capillary pressure curves for cores tested in FY88.

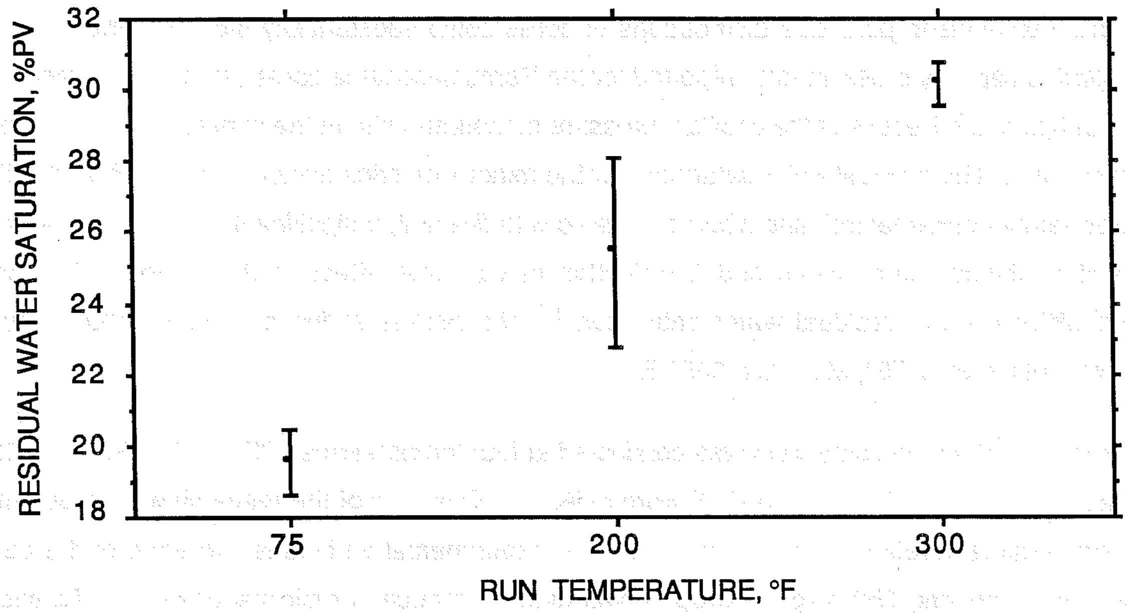


FIGURE 3. - Residual water saturations from capillary pressure curves for cores tested in FY89.

## Evaluation of Silylated Cores

To evaluate the thermal and hydrolytic stability of the porous materials prepared by gas phase silylation, a number of tests were conducted to establish if the silylation was permanent. The initial apparatus designed to silylate cores yielded cores that had an external oil-wet coating but were not appreciably different from the original cores as shown in table 1. To complete the bonding of the silane to the silicon core surfaces requires a minimum of 527° F. A stainless steel pressure vessel that can be heated in a tube furnace was constructed in order to conduct these reactions. Additional silylations were conducted at these elevated temperatures. Visual observation of the core after the silylation shows a dark grey color. Wettability experiments on these newly silylated cores (using the New London crude oil, table 2) demonstrates that the new procedure ensures bonding of the silane and results in oil-wet cores. Silylated cores 1 and 2 (table 2) were refluxed in water in a Dean Stark extractor whereas silylated cores 3-6 are the base case silylated cores from the higher temperature treatment. The oil-wet character survives both 100 pore volumes of water equivalent steam during steam injection (cores 7,8) and oil saturation followed by steam flooding (cores 9-10 as obtained from the injection and production ends of run 4 of a 1-D steamflood, Chapter 2). There is nearly a direct correlation between the severity of the steam treatment and the increase in wettability. Silylated cores steamed at higher temperatures with larger pore volumes of steam injected become the most water-wet.

TABLE 1. - Wettability of low temperature silylated cores

| Core No. | Wettability value |
|---|---|
| 1 | +0.37 |
| 2 | +0.34 |
| 3 | +0.55 |
| 4 | +0.41 |
| 5 | +0.42 |
| 6 | +0.44 |

Cores 1-3 were fired; cores 4-6 unfired, cores 3 and 6 had Dean Stark.

TABLE 2. - Wettability of high temperature silylated cores

| Core No. | Additional treatment after silylation | Wettability value |
|---|---|---|
| 1 | 48 hr Water reflux, 205°F | -0.41 |
| 2 | 48 hr Water reflux, 205°F | -0.48 |
| 3 | None | -0.58 |
| 4 | None | -0.82 |
| 5 | None | -0.85 |
| 6 | None | -0.63 |
| 7 | 8 hr Steam at 335-365°F | +0.093 |
| 8 | 8 hr Steam at 285-335°F | -0.29 |
| 9 | 1-D steamflood core at 350°F - injection end | -0.52 |
| 10 | 1-D steamflood at 350°F - production end | -0.42 |

## CONCLUSIONS AND RECOMMENDATIONS

In conclusion, additional experimentation performed during FY89 has shown that at the 95% confidence level, residual water saturations for nitrogen/brine, mineral oil/brine, and crude oil/brine systems are significantly different, and an increase in temperature in capillary pressure experiments corresponds to an increase in residual water saturation (in Berea core). Additional capillary pressure data will be generated in this project on other rock matrices in an effort to quantify expected oil recovery from EOR processes that are associated with reservoirs at elevated temperatures.

A method for preparing oil-wet cores was developed. The thermal and hydrolytic stability of the treated surface have not been quantified and further evaluation is necessary.

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# CHAPTER 4 - COMPARE EXPERIMENTAL STEAMFLOODING INFORMATION OBTAINED DURING FY 84 THROUGH FY 88 WITH PREDICTED VALUES BASED UPON FUNDAMENTAL PRINCIPLES, TASK 4.

## OBJECTIVE

Compare experimental steamflooding information obtained during FY84 through FY88 with predicted values based upon fundamental principles.

## BACKGROUND

The primary objective of task 4 is to develop a research-oriented thermal simulator that can rigorously model the complex phenomena that occur during the steamflooding of light oil reservoirs and to perform sensitivity studies to determine factors controlling the laboratory steamflood process.

Several thermal EOR simulators exist in the private sector.[1-3] The purpose of the present modeling effort is not to compete with the more general thermal simulator in the private sector, but rather, to provide the researcher with a modeling tool capable of running on a personal computer which can be used in the planning and interpretation of laboratory experiments.

## SCOPE

Work for task 4 in BE11A and in the corresponding task number 3 in BE11B is the development of a thermal numerical simulator to aid in the planning and interpretation of laboratory steamflooding results.

## SIMULATOR STATUS AND DISCUSSION

### Thermal Simulator Model Description

The thermal simulator is a numerical model shown schematically in figure 1 which solves the fundamental equations describing the compositional multiphase thermal EOR process. The model is capable of describing laboratory-scale hot waterfloods and steamfloods. The seven fundamental equations employed in the model are for a system of four components distributed among three phases. Distillation effects are simulated by assuming the oil-phase consists of up to three volatile components. The distribution of the volatile component among the phases is dictated by vapor-liquid equilibria. Energy is transferred and accounted for by the mechanisms of convection and conduction, and by energy changes associated with condensation and vaporization.

The seven partial differential equations (PDE) that describe the conservation of mass, conservation of energy, and constraints on sum of phase-saturation and on sum of the liquid and gas-phase mole fractions are similar to those used by Coats,[1] and we have described them previously.[4] The mass conservation equations apply to water and to each of the three hydrocarbon components. All physical properties are allowed to be functions of pressure, temperature, and/or composition. The unknowns in the model are $P_o$ (oil-phase pressure), T (temperature), $S_g$ (gas-phase saturation), $S_w$ (water-phase saturation), and oil component mole fractions (x 1, x 2, and x 3).

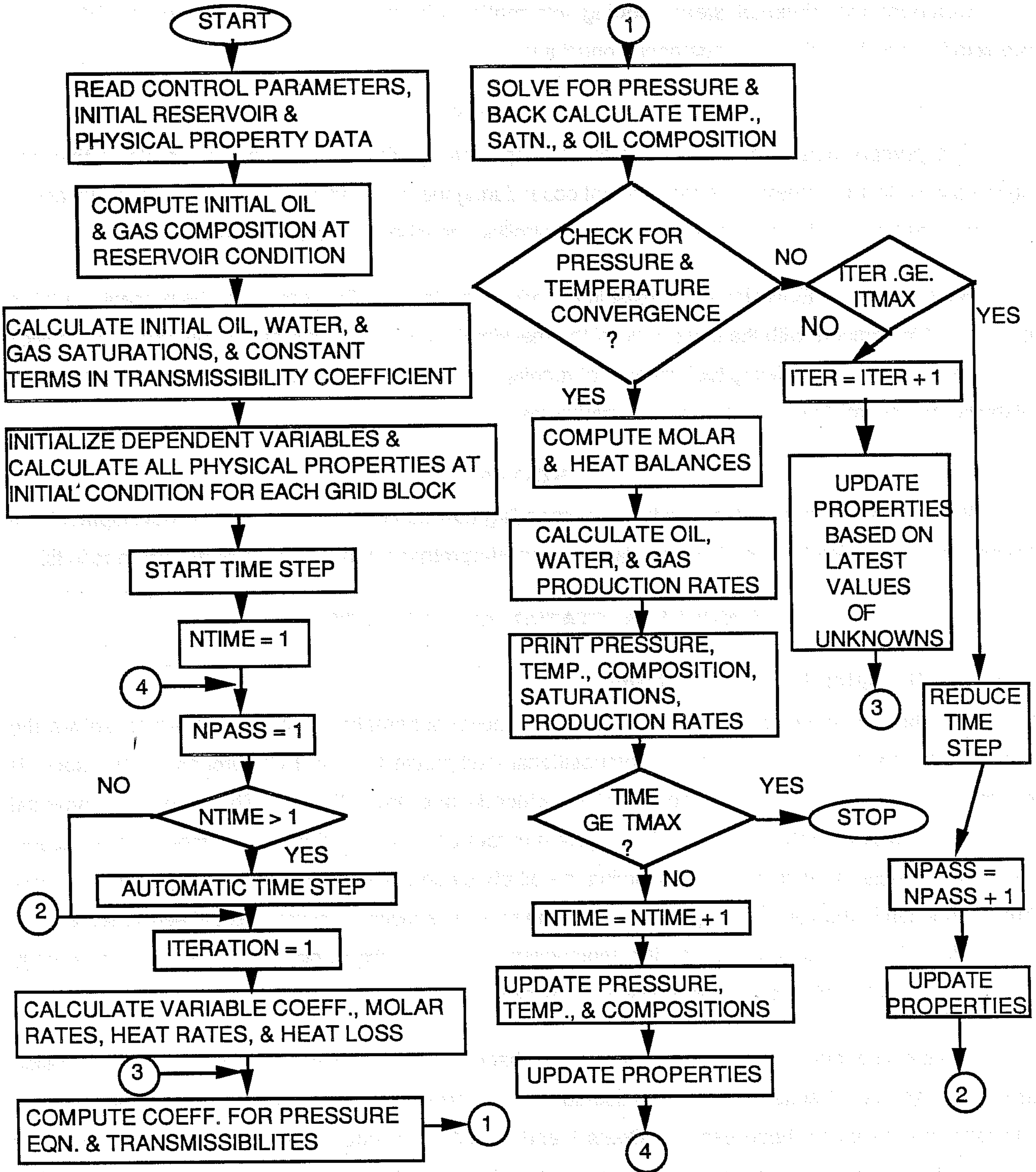


FIGURE. 1. - Schematic of logic in laboratory thermal numerical simulator.

## Numerical Techniques

The model's numerical solution technique is based on a block-centered, finite-difference method. The reservoir is divided into a number of grid blocks. The finite-difference representations of the seven fundamental partial differential equations are evaluated in each reservoir grid block. The equations are discretized using standard central difference approximations in space and two-point backward differences in time. Upstream weighting is used with the transmissivity and transconductivity terms. All properties are implicitly dated (based on the current time-step variable).

The discretization yields seven coupled nonlinear algebraic equations per grid block. In expanding the PDE in finite-difference form, the changes or increments over the time-step were used rather than the total values as the unknowns. This way of expansion adds more stability to the formulated model. These $7 \times N_G$ equations, where $N_G$ = number of grid blocks were solved simultaneously using the procedure described by Ferrer and Ali.[5]

## Boundary and Initial Conditions

Certain initial and boundary conditions must be specified in order to complete the description of the numerical model. Initial conditions require specification of all dependent variables throughout the solution domain at time, $t = 0$. In addition, any rock and/or fluid properties not dependent on dependent variables must also be specified in the domain. In the model, initial conditions are deemed to be specified if the following variables are defined in each grid block of the domain: k (permeability), $\phi$ (porosity), $P_o$ (oil-phase or initial reservoir pressure), T (temperature), $S_o$ (oil saturation), $S_w$ (water saturation), and $x_i$, $i = 1,2,3$ (mole fraction of hydrocarbon components in oleic-phase). Specification of these variables allows all other variables to be initialized when the various constraint equations, vapor-liquid equilibrium relationships, and other rock-fluid property functionalities are applied.

Boundary conditions require the specification of the dependent variables around the reservoir boundary at all times. In the present model, no flow boundary conditions are specified; i.e., the model assumes no flow of material or energy across the reservoir boundaries. Numerically, this is accomplished by setting the transmissivities and transconductivities in the boundary grid blocks equal to zero.

## Source and Sink

In the model, a well is considered as a source if it is an injection well and as a sink if it is a production well. An injection well is described by specifying its location, and the temperature, pressure, quality, and injection rate of the steam as a function of time. On the production side, the well is specified by a bottom-hole backpressure and a productivity index. The relative amount of phases produced are not subject to control as in the case of the injection wells. They are functions of saturation in the grid blocks containing the well. The rate of production of each phase is assumed to be proportional to the local mobility of that phase. The relative amount of components produced are functions of pressure, temperature, phase saturation, and component mole fraction in the grid block containing the well.

## Automatic Time-Step Adjustment

Time-step size adjustment is required because the time rate of change in the primary variables vary significantly during a simulation run. The approach used in this study was to choose a time-step based on variable changes across the previous time-step according to

$$\Delta t_i^{N+1} = \frac{2\Delta\psi_i \Delta t^N}{\Delta\psi_i + \delta\psi_i}$$

Where $\Delta\psi_i$ is read from input and $\delta\psi_i$ is the maximum change in the dependent variable, i, over all grid blocks across time-step $\Delta t^N$. The new time step is the minimum of all $\Delta t_i$'s as long as $\Delta t_{min} < \Delta t < \Delta t_{max}$. $\Delta t_{min}$ and $\Delta t_{max}$ are the minimum and maximum permissible time-step sizes for the simulation run. $\Delta t_{min}$ and $\Delta t_{max}$ are read from input.

## Treating Phase Disappearance

The number of phases present are not the same in all grid blocks, and phases may appear and/or disappear in any block during the simulation. For example, when steam enters a cold block whose temperature is well below the steam saturation temperature, steam will condense and results in the disappearance of the vapor phase. The rigorous treatment of phase disappearance requires a reformulation of the conservation equations during phase disappearance. In this study, the pseudo k value approach of Crookston et al.[3] was used to avoid the difficulties and assumptions required in switching formulation. By this approach, we adjust the k value by multiplying it with a factor so as to create a situation in which individual phases are not allowed to disappear completely but a small saturation of each phase is maintained at all conditions.

## Convergence Criteria

The simultaneous solutions are iterated until all dependent variables in all grid blocks satisfy the convergence criteria or until a maximum iteration count is exceeded. The convergence criteria are met if the absolute difference between the old and current iterated values are less than a specified tolerance. If convergence is not obtained within a specified number of iterations, the calculations are repeated after the time-step is halved. If the number of interval halvings is exceeded without convergence, the simulation stops.

### Other Computations

Heat loss to the surroundings is calculated assuming one-dimensional heat flow in the direction perpendicular to the fluid flow. For this purpose, a direct solution of the finite-difference representation of the heat equation is employed. The solution is used to compute the heat loss rate that enters into the heat balance. Incremental molar and heat balances are performed at each time-step.

### Simulation Output

The output from the simulation provides extensive information for evaluating the performance of the steam injection process. This information includes the tracking with time and position of pressure, temperature, phase saturations, phase mole fractions, and instantaneous phase and component production rates.

### Simulator Validation

A hypothetical problem was designed to debug the simulator. Because of the complexity of the problem and nonlinearity of the coefficients for pressure, temperature, composition, and saturation, computational difficulties were encountered. These included numerical oscillation in the saturation values and unacceptable material balance errors. Investigation of the potential source of error indicated that these difficulties arose basically due to the IMPES nature of the formulation and explicit treatment of transmissibility (interblock flow terms). Steamflood transmissibility is not only a function of saturation, but also of temperature and composition. This functional dependency of the interblock flow term on several variables prevented the linearization of these terms without simplifying assumptions. Further computational difficulties were encountered because of the occurrence of nonlinearities such as potential reversal and overshoot (negative saturation). These problems were solved to some extent by reformulating the governing equations, adding first order approximations to transmissibility and treating source and sink terms implicitly. Resulting equations were then solved sequentially by a reduced band-width direct solution technique.

When tested using a small but reasonable time step, the revised model exhibited adequate stability and gave acceptable material balance errors. As pointed out by other researchers,[1,6] only a fully implicit steamflood model is capable of overcoming material balance shortcomings and yielding stable solutions. However, this is also the most expensive method for obtaining the solution in each time step. Further, a fully implicit formulation drastically increases the complexity of the model and storage requirements. Because of memory limitations, it is not possible to code and test a fully implicit compositional steamflood simulator on a personal computer. Since the objective of this task is to develop a tool to aid in the interpretation of the laboratory results, development of a more complex model is not warranted. However, efforts are being made to improve the performance of the current model.

Numerical model runs were conducted using two test cases. The purpose of these runs was to qualitatively examine the behavior of the numerical model in solving published test problems. In the first problem, the model's temperature distribution was compared with the experimental values of Malofeev[7] for horizontal flow of steam in a water saturated sandpack. In the second problem, the model's temperature and oil recovery data were matched with the experimental data of Willman et al.[8] for a linear 1-D steamflood. In figure 2, the model temperature profile is compared with Malofeev's[7] experimental data and Spillette's[9] predicted values. The model prediction lies below the laboratory case indicating that the heat losses assumed in the numerical model were too large. However, keeping in mind the differences between the two cases, the behavior between the numerical and physical models is qualitatively similar. Willman et al. carried out a number of one-dimensional steamflood and hot water injection studies in cores. For one set of experiments, they reported temperature distributions, and Shutler[10] presented the corresponding oil recovery from their simulator's match of the temperature and oil recovery data, employing Weinstein et al's.[11] proposed set of rock, fluid and thermal data. We used this data set in our attempt to simulate their laboratory results.

Figure 3 shows a calculated temperature profile that shows the NIPER model underpredicted the temperature. In figure 4, the calculated and experimental oil recovery are compared and show that the general character of the curves is similar, but the NIPER simulator failed to match the experimental oil recovery. This can be attributed to simulator heat loss being too large and suspect rock fluid data.

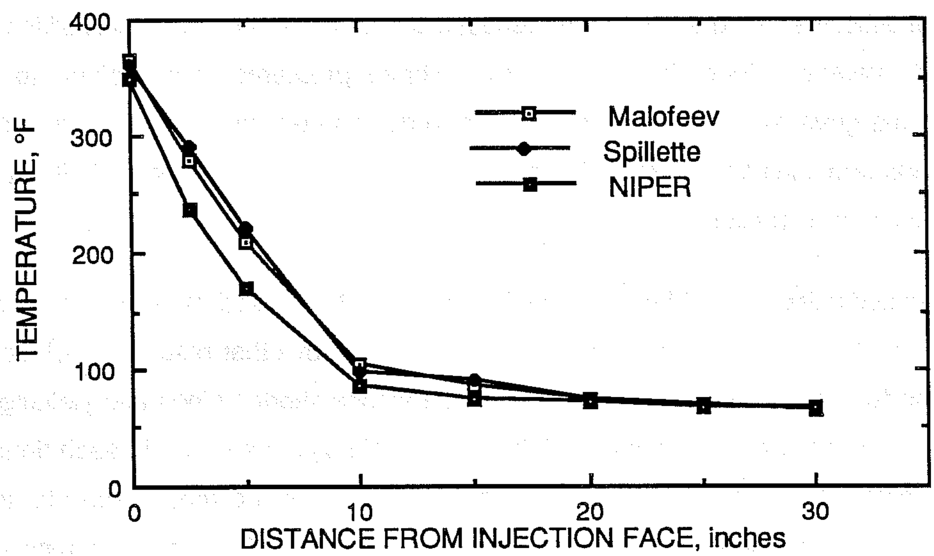


FIGURE 2. - Temperature distribution after 1 hour of steam injection.

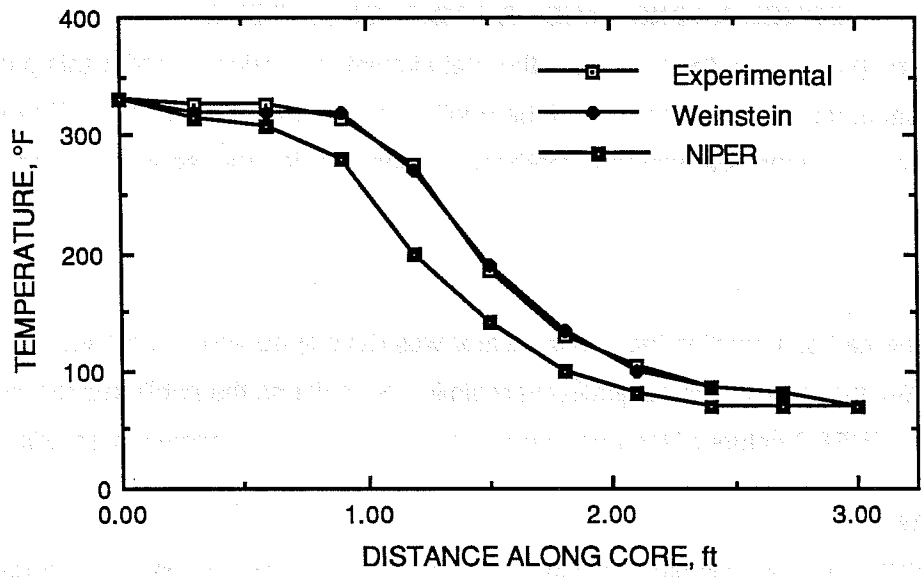


FIGURE 3. - Comparison of simulated and experimental temperature profiles for laboratory model after 2.5 hours of steam injection.

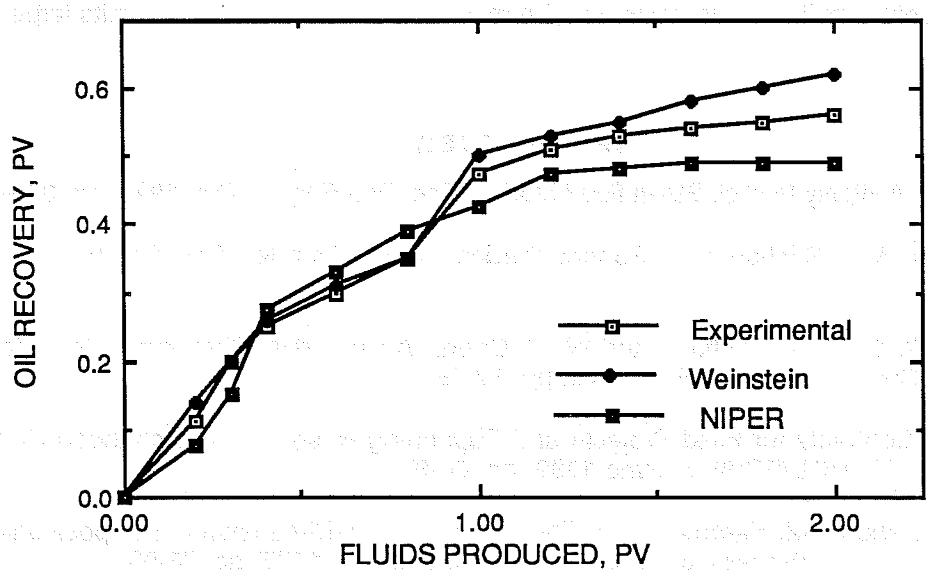


FIGURE 4. - Calculated and experimental oil recovery curves for laboratory experiments.

## CONCLUSIONS AND RECOMMENDATIONS

Based upon the progress of the numerical thermal simulator developed under this program and under BE11B, a topical report on the simulator will be published under BE11B in FY90. The topical will include the governing equations, derivations, methods of solution for the equations and sensitivity studies.

### Conclusions

1. A research-oriented composition thermal simulator was developed and debugged.
2. The results from the model showed qualitatively similar behavior as the published results.
3. Because of the IMPES nature of the formulation, the model exhibits conditional stability.

### Recommendations

1. Continue in FY90 the research effort to improve model performance and predictive ability.
2. Examine alternative formulation and solution schemes, for implementation in the simulator. Possible examples of these schemes include the Newton-Raphson iteration scheme to solve the set of nonlinear equations at each time-step.
3. Explore avenues for making the model more implicit without increasing the complexity of the model. A highly implicit model improves the material balance error and permits larger time-step size.

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## CHAPTER 5. - SUPPORT THE DOE IN ITS COOPERATION WITH VENEZUELA BY PRESENTING RESULTS OF THIS PROJECT (BE11A) AT THE ANNEX IV MEETINGS, TASK 5.

### OBJECTIVE

The objective of this task is to support the U.S. Department of Energy in technology transfer with the Ministry of Energy and Mines of the Republic of Venezuela in the area of thermal oil recovery with emphasis on light oil.

### BACKGROUND

#### Annex IV Between U.S. DOE and Ministry of Energy and Mines, Venezuela

Annex IV between the U. S. Department of Energy and the Ministry of Energy and Mines, Venezuela is designed for technology transfer between the countries in the area of thermal oil production. Each country is to pursue its own research, but the Annex is designed to minimize duplication of efforts and advance the technology. The Annex promotes cooperation of the researchers and open discussion of the technical problems facing both laboratory and field development of thermal processes for oil production.

### RESULTS AND DISCUSSION

The Annex IV meeting was held in conjunction with the Third International Symposium on Enhanced Oil Recovery in Maracaibo, Venezuela, February 19-14, 1989. The paper, "Two-Dimensional Steamflood Laboratory Studies of Light Crude Oil Saturated Sandpack -- Comparison of Waterflooded With Nonwaterflooded Porous Media," by P. Sarathi, S. D. Roark, and A. Strycker was presented by D. Olsen. Following the meeting, the Annex IV annual meeting was held wherein the U.S. Department of Energy and its contractors, and the Ministry of Energy and Mines of Venezuela with its research group, INTEVEP, exchanged technical information on thermal oil production. Contractors proposed research that they would like to pursue in the coming year, and an extension of the Annex for the next 18 months was formulated. Two reports that summarize NIPER research on BE11A during the past year were submitted to DOE for inclusion in the proceedings of this meeting which DOE publishes. The reports delivered were as follows:

- NIPER Paper No. EPR/OP-88/23 by Partha Sarathi, S. Doug Roark and Arden Strycker, "Two -Dimensional Steamflooding Laboratory Studies of Light Crude Oil Saturated Sandpack -- Comparison of Waterflooded with Nonwaterflooded Porous Media" presented by David Olsen, February 19, 1989.[1]

- NIPER-338 by Arden Strycker and Partha Sarathi, "Steamflooding Light Crude Oil Reservoirs -- a State-of-the-Art Review, April 1988.[2]

A report is being prepared to account for research on light oil steamflooding at the semiannual Annex IV meeting on October 12-13, 1989, at Stanford University, Stanford, California.

## CONCLUSIONS AND RECOMMENDATIONS

Annex IV follows not only the guidelines but also the intent of the technology transfer. The published record of the proceedings and the goals of each project, the methodology within the research, and the conclusions from the research are discussed openly and frankly with the intent of advancing the technology. The meetings build working relationships between researchers in each country, between countries, and between field operations and research staff. It provides a relationship of cooperative effort to solve not only laboratory operational problems at the meetings but also throughout the year.

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